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WATER TUNNEL TESTS
OF THE
BRITISH SQUID
PROJECTILE TYPE "C"

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by

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WATER TUNNEL TESTS
OF THE
BRITISH "SQUID" PROJECTILE TYPE C

(Laboratory Designation ND 24)

GENERAL DESCRIPTION

This report covers Water Tunnel tests on a 2" diameter model of the "Squid" or British Type "C" Projectile. These tests were conducted for the purpose of determining the performance characteristics of the projectile as well as cavitation effects with varying water pressures. The work was done at the joint request of the British Admiralty Delegation and the Bureau of Ordnance.

Appendix "A" gives a description of the various terms and symbols used, as well as a brief discussion of the requisite conditions for stability in a projectile. Appendix "B" gives a description of what has been termed the "Characteristic Chart". This is useful in determining the relative performance of various modifications in the design.

All curves of observed data have been faired and corrected for interference.

DESCRIPTION OF PROJECTILE

Figures 1, 2, and 3 show details of the model of the projectile with the eight vane tail assembly. The general dimensions of the model are:

Diameter	2"
Length overall	9.26"
Scale ratio	5.95

Prototype Data:

Diameter	11.9"
Total weight in air	386.4 lbs
Total weight in sea water	234 lbs
Distance from nose to	
Center of gravity in air	20"
Center of gravity in sea water	18.4"

Figure 1

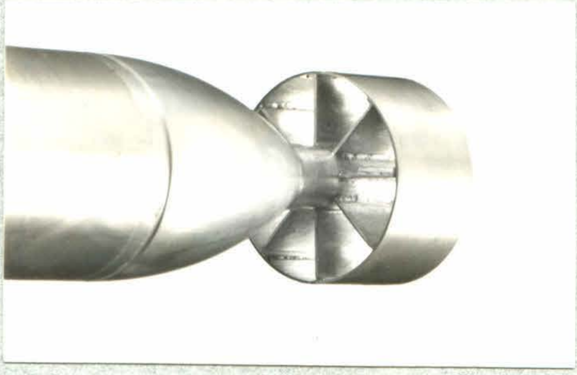


Figure 2

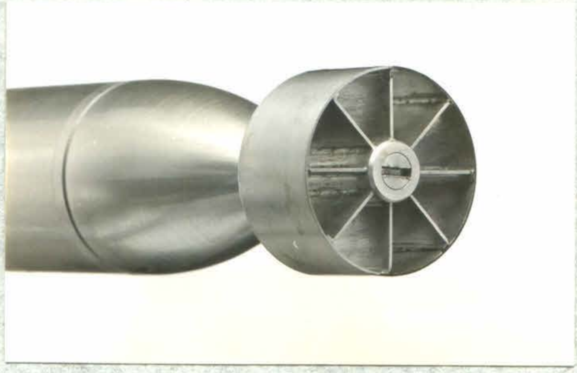


Figure 3

Photographs of Model
British Type "C" Projectile

PERFORMANCE CHARACTERISTICS

Tests were made on the model in the High Speed Water Tunnel to determine the drag, cross force, and moment for values of yaw angle varying from $-10°$ to $+10°$. From these observed data were calculated the drag and cross force coefficients and the moment coefficient about the center of gravity. For the moment coefficient the center of gravity in air was used. Curve sheet, Figure 4, shows the values of the coefficients and CP eccentricity varying with the yaw angle.

The Characteristic Chart, Figure 5, gives the relations between drag coefficient, moment coefficient divided by the yaw angle, and CP eccentricity. From this chart it is seen that the projectile has a low drag coefficient (not exceeding 0.31 at 10° yaw) and that the CP lies a little over 11% of the length aft of the CG. It is also seen that the restoring moment increases at a constant rate with increasing yaw angle. These conditions indicate that the projectile has a fair degree of stability.

TERMINAL VELOCITY

In order to extrapolate the diagram measurements on the model to prototype scale, drag coefficients were determined with velocities in the Tunnel varying from 10 to 54 feet per second. The results are shown as dots on curve sheet, Figure 23, in which the drag coefficients are plotted against Reynolds number, R. In this calculation R is defined as:

$$R = \frac{VL}{\nu}$$

where

V = Velocity of projectile in feet per second

L = Length of projectile in feet

ν = Kinematic viscosity of water in sq ft per sec

By extending the curve, fitted to the experimental points, the drag coefficients for higher Reynolds numbers are obtained.

When the prototype projectile reaches its terminal velocity, its weight in water is equal to the drag force on the body. By using this relationship, the formula for the drag coefficient and the drag curve, Figure 23, the terminal velocity can be calculated. This calculation gave a terminal velocity for the prototype of 36.9 feet per second with a corresponding drag coefficient of 0.224. The Reynolds number for the terminal velocity of 36.9 feet per second is found, by the above formula, to be 1.52×10^7. In these calculations the weight of the bomb in sea water was used and the temperature of the sea water was assumed to be about 70 degrees Fahrenheit. As the extrapolation is not great and the observed data do not depart much from a straight line, it is believed that the calculated values for the prototype are fairly reliable.

CAVITATION TESTS

A series of photographs was made of the model in the Water Tunnel showing a wide range of cavitation effects. These photographs are Figures 7 to 19 inclusive and have been arranged, by inspection, in accordance with the degree of cavitation. Curve sheet, Figure 20, shows the cavitation parameter, K, corresponding to each photograph in the series.

The tests were made by maintaining a constant water velocity of 40 feet per second in the Tunnel and varying the water pressure by small increments. A photograph was taken for each value of the pressure after conditions became stable.

It is instructive to examine the photographs in relation to Figure 21 which gives the variation in drag with the cavitation parameter. The amount of cavitation that can be seen appears to be very slight, although the effects are great. Figure 21 shows that the drag suddenly increases at an enormous rate when K has dropped below a value of 1.25. This point corresponds approximately to the condition shown in Figure 8 where the cavitation effect is hardly noticeable.

The violent increase in drag caused by what appears in the photographs to be slight cavitation is well illustrated by comparing Figures 10 and 12 with Figure 7. In the condition represented by Figure 10, the drag has been increased 50% over that of Figure 7, the point of incipient cavitation, and in the condition represented by Figure 12, the drag has been approximately doubled.

What appears to be a slight haze above the model in Figures 7 to 10 is not due to halation in the photograph, but is caused by the fine bubbles of vapor being swept away from the cavitation zone at the nose.

In Figures 11 to 14 the cavitation effect appears to be confined to the upper part of the model. It is probable that this is largely due to interference set up by the support shield, although it must be borne in mind, the conditions for cavitation being so critical, that the slight difference in pressure between the top and bottom of the model cannot be ignored.

It is observed that the model is completely enveloped in the cavitation bubble in Figures 17, 18, and 19. This would correspond to the state of the projectile during the first portion of its trajectory after entrance.

CAVITATION AND DRAG

A series of tests was made to determine variation in the drag coefficient with different values of the cavitation parameter, K, in all cases the water velocity being maintained at 40 feet per second. The results of these tests are given in Figure 21. This curve shows that incipient cavitation occurs at a value of K = 1.76 with a drag coefficient for the model of 0.232 and a gage pressure of 4.6 pounds per square inch. At practically zero gage pressure the drag coefficient started to increase rapidly with reduced values of K, and with a gage pressure of -5.5 pounds per square inch and a value of K = 0.82, the drag coefficient increased to 0.34. Under this condition the cavitation effect extended about 1/2 inch back from the nose (i.e., 1/4 diameter) or practically as shown in the photograph, Figure 10.

There is evident a definite, though small, decrease in drag with decreasing values of K in the early stages of cavitation. Apparently this results from a reduction in skin friction caused by the envelope of vapor being formed around the model. This is a well known phenomenon that has been observed in the testing of pumps and turbines.

The cavitation parameter, K, is defined as follows:

$$K = \frac{P - P_v}{\rho \frac{V^2}{2}}$$

in which

P = Absolute static pressure in lbs per sq ft

P_v = Vapor pressure, at the corresponding water temperature, in lbs per sq ft

ρ = Mass density of the fluid in slugs per cu ft = $\frac{w}{g}$

w = Specific weight of the fluid in lbs per cu ft

g = Acceleration of gravity in ft per sec^2

V = Velocity of the projectile in ft per sec or velocity of the water, in model tests.

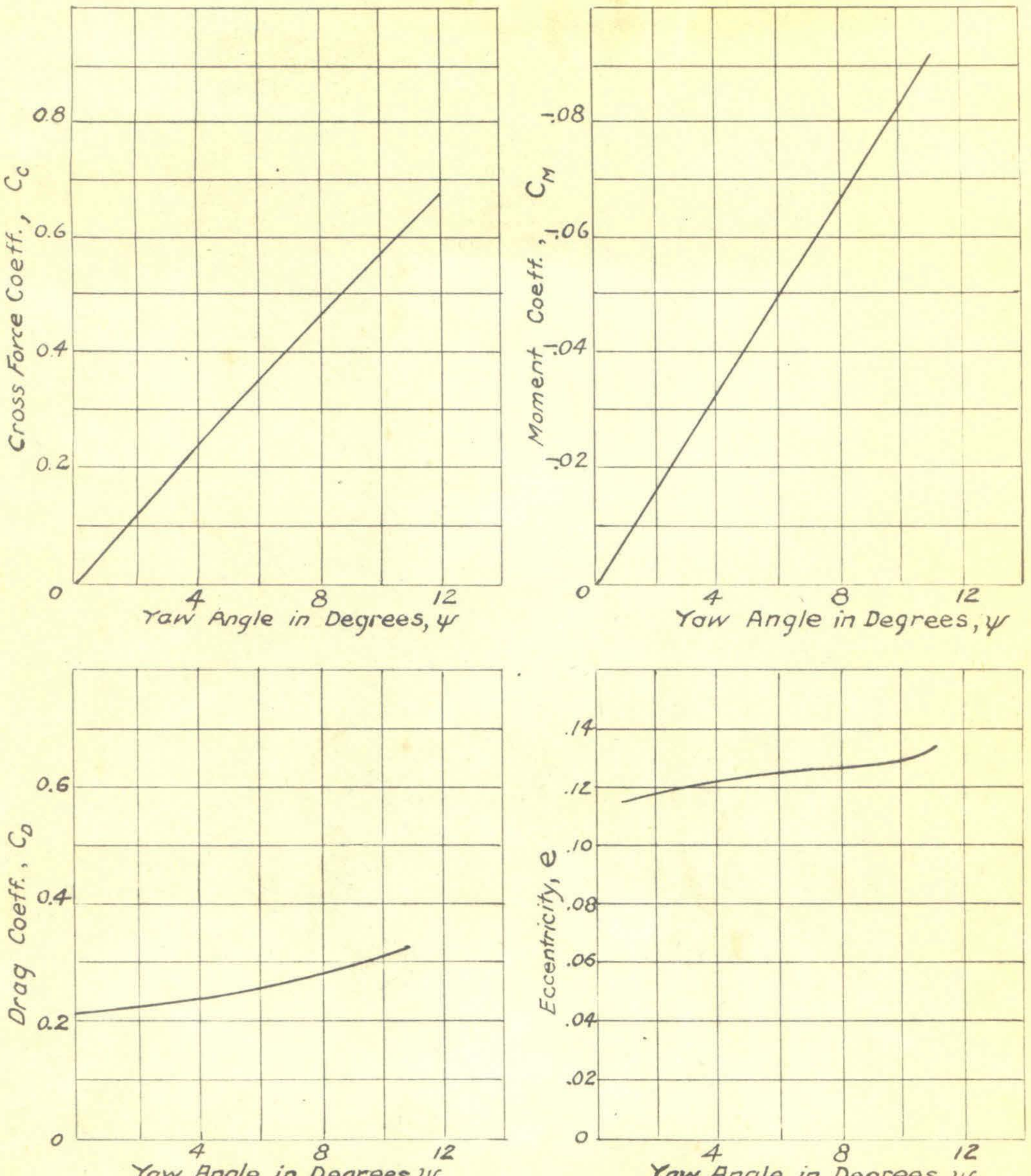
CAVITATION AND SUBMERGENCE

It is understood that this projectile enters the water at a velocity of approximately 160 feet per second at an angle of 45°. Bodies with hemispherical noses appear to have an effective drag coefficient of about 0.67 at entrance, and for this discussion it is assumed that this value applies to the "Squid" also. Assuming further that the drag coefficient decreases linearly with increasing values of the cavitation parameter, K, and that it reaches a terminal value for the prototype of 0.224 when K = 1.25, the velocity-depth relationship can be calculated. The results of these calculations are shown in Figure 22, which gives the relation between submergence, velocity, and K up to a value of K = 1.76 which is the point of incipient cavitation. The shaded area indicates the region in which cavitation does not take place.

In Figure 22 is also shown a curve of estimated projectile performance based on the simplifying assumption that the trajectory remains at a 45° angle after entrance. It will be seen from this curve that rather violent cavitation is to be expected until the projectile has travelled to a depth of 17 feet (K = 0.7) and has had a reduction in velocity to 65 feet per second. It is probable that this means the entrance bubble will not be swept away until after this point is reached, as the vaporization from the cavitation will keep feeding gas to the void.

In calculating the performance of the projectile after entrance, it was assumed that the pressure in the bubble was equal to the vapor pressure. It is probable that the pressure is much greater than this due to the air entrained at entrance.

It is interesting to study the photographs in their relation to the curves in Figure 22. The photograph corresponding to various points on the dotted curve of projectile performance can be identified by means of the cavitation parameter. It should be remembered that the photographs represent the minimum condition to be expected as discussed in the foregoing paragraph.



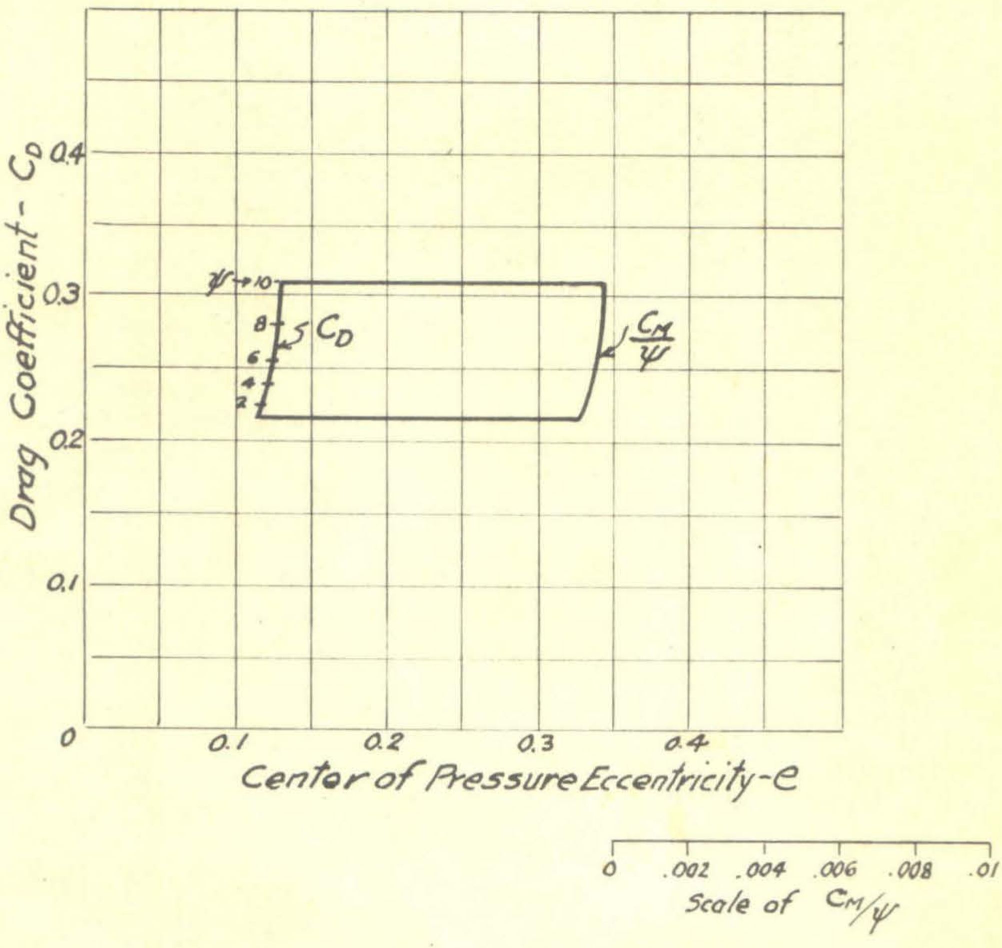
FORCE COEFFICIENTS and
CENTER of PRESSURE ECCENTRICITY

British Type "C" Projectile

CIT - HML
DRG - ND 24 - 1632 - LS

Fig 4

SECRET



CHARACTERISTIC CHART
British Type "C" Projectile

CIT-HML
DRG-ND24-1633-LS

Fig. 5

SECRET

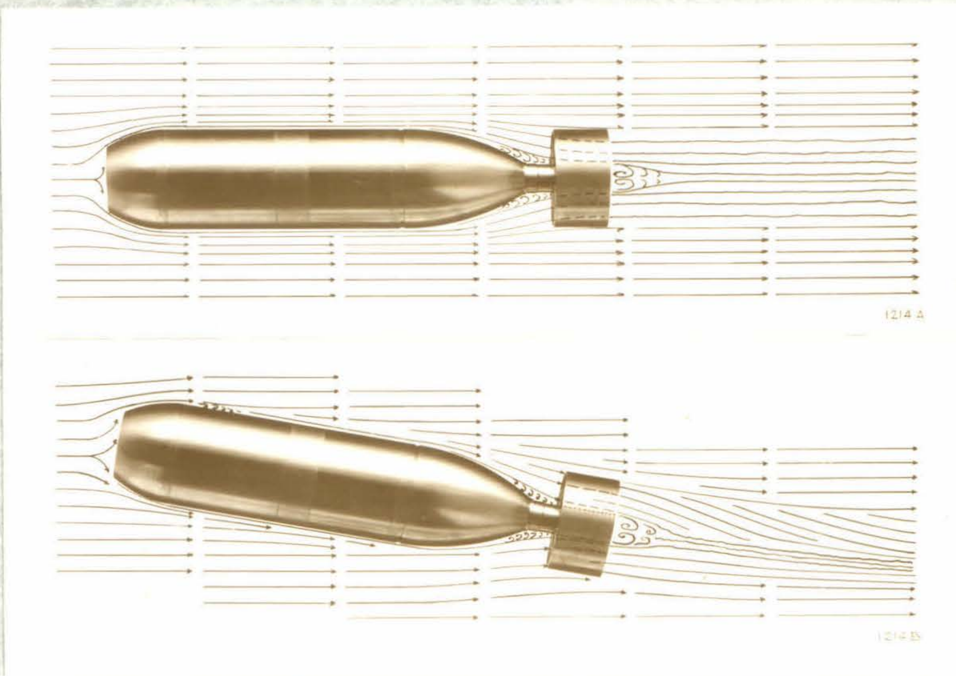


Figure 6

FLOW DRAWINGS

The above flow drawings show the flow around the model as observed in the Polarized Light Flume. The model is shown at 0° and 12° yaw. It is to be noted that there is very slight turbulence at the square nose and only nominal turbulence in the wake of the eight-vane tail. These effects are consistent with the low drag coefficient observed for this model.

FIG. 7
K = 1.628

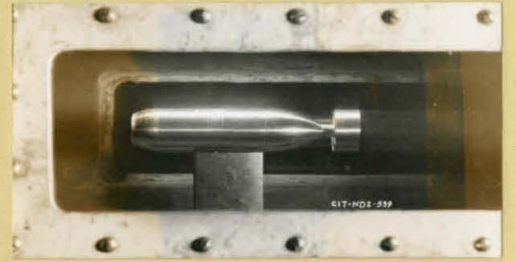


FIG. 8
K = 1.303

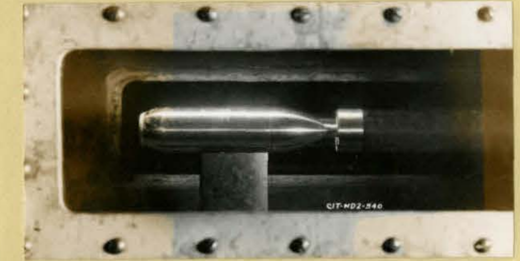


FIG. 9
K = 1.026

FIG. 10
K = 0.814

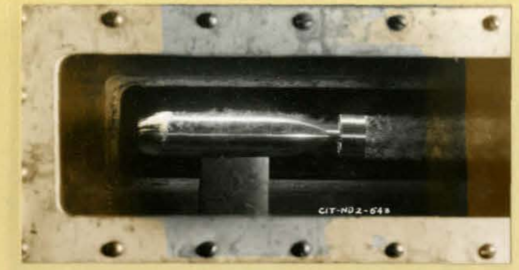


FIG. 11
K = 0.678

FIG. 12
K = 0.523

FIG. 13
K = 0.470

FIG. 14
K = Not determined

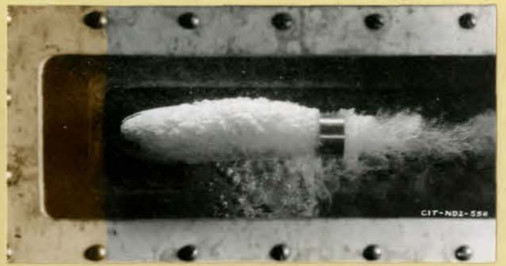


FIG. 15
K = 0.393

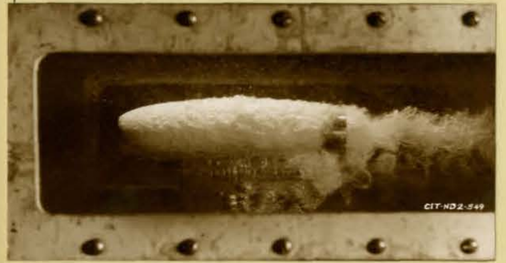


FIG. 16
K = 0.374

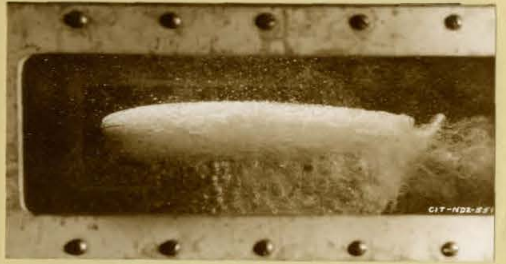


FIG. 17
K = 0.459

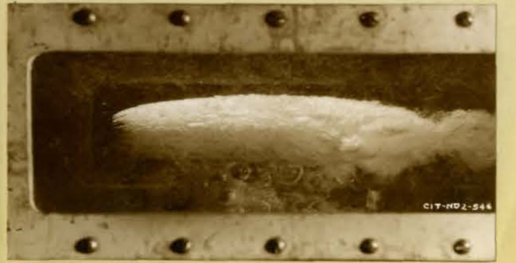


FIG. 18
K = 0.382

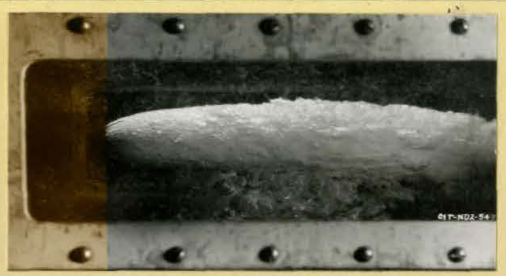


FIG. 19
K = 0.368

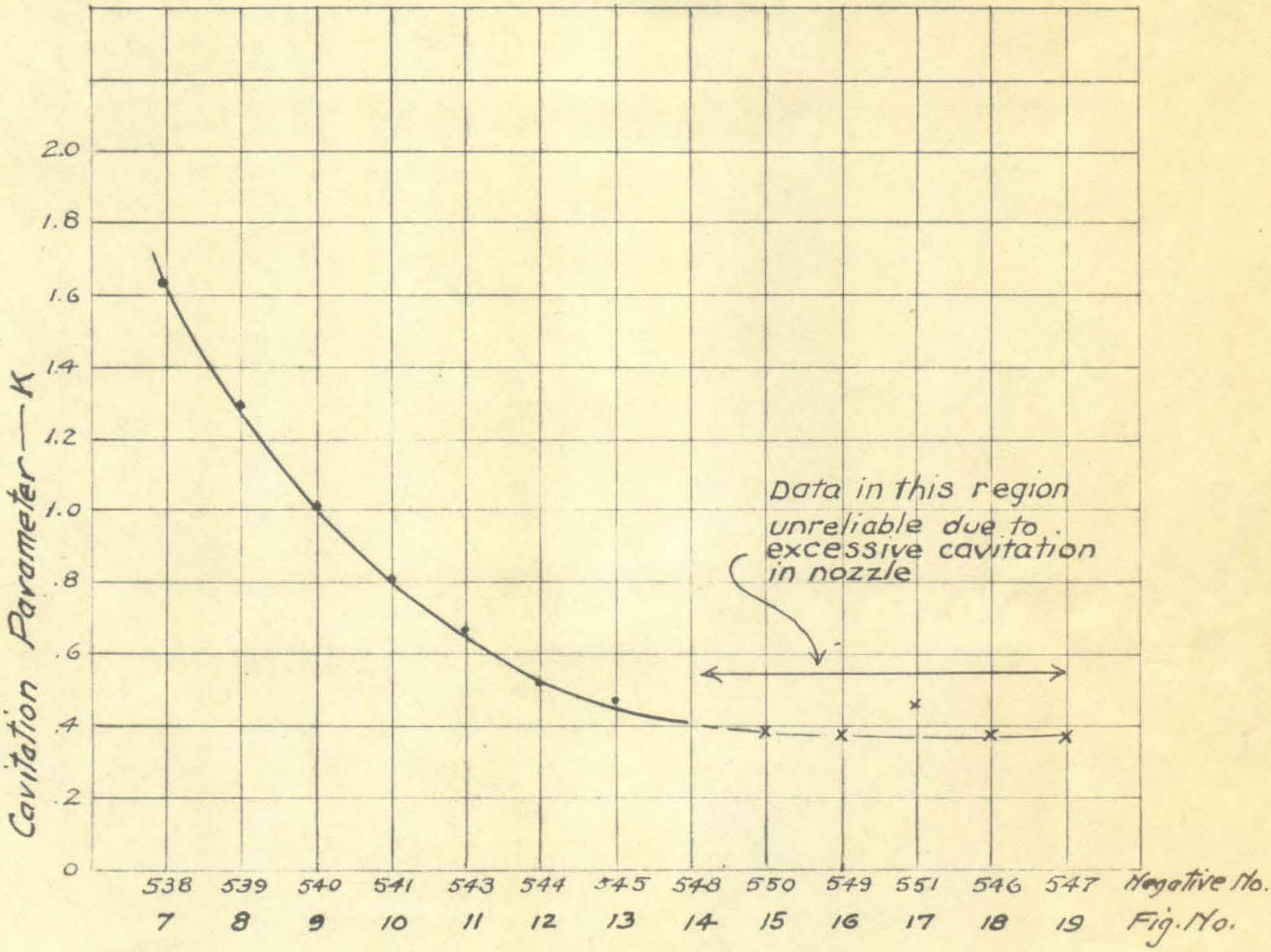
NOTE: Photographs have been arranged by inspection according to the degree of cavitation.

DATA: Water Velocity - 40 ft per sec.
Water Temp. - 70.6°F
Barometer - 29.34"

PHOTOGRAPHS OF CAVITATION TESTS

British Type "C" Projectile

CIT-HML
DRG.-ND24-1635M

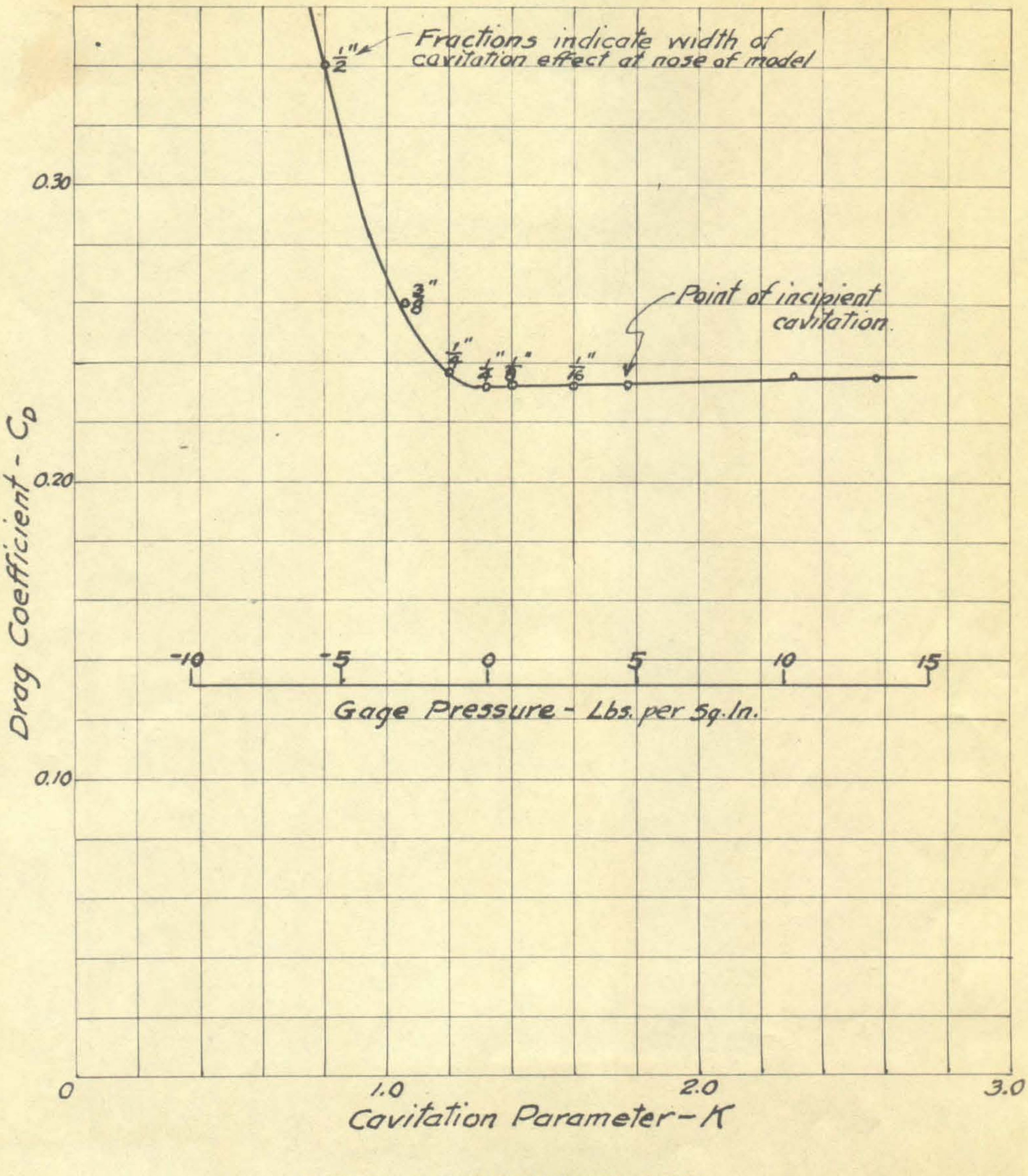


CAVITATION PARAMETERS
AND PHOTOGRAPH NUMBERS

British Type "C" Projectile

CIT-HML
DRG-NO 24-1634-LS

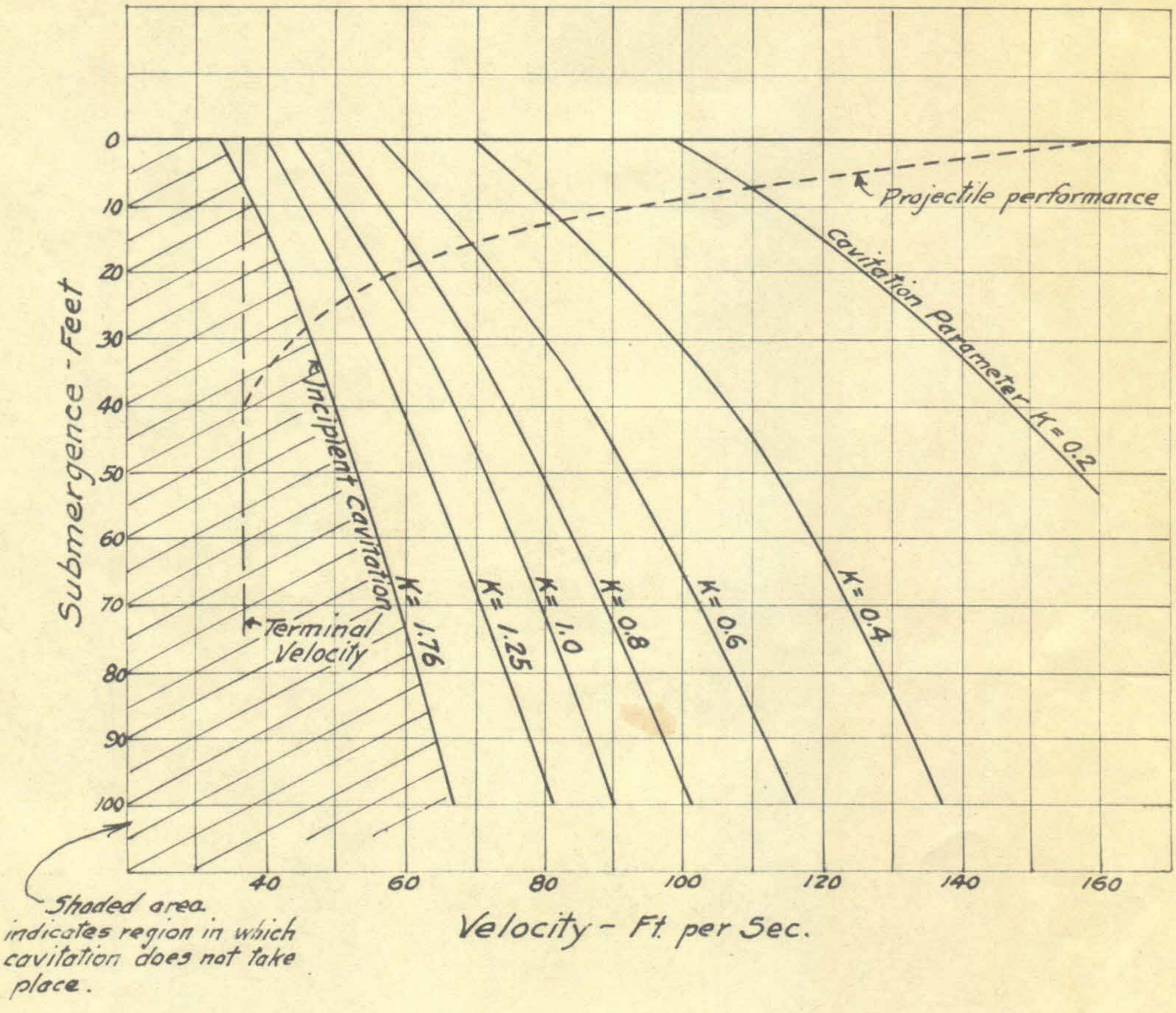
Fig. 20



DRAG COEFFICIENT AND CAVITATION PARAMETER

British Type "C" Projectile

CIT-HML
DRG-M024-1668LS

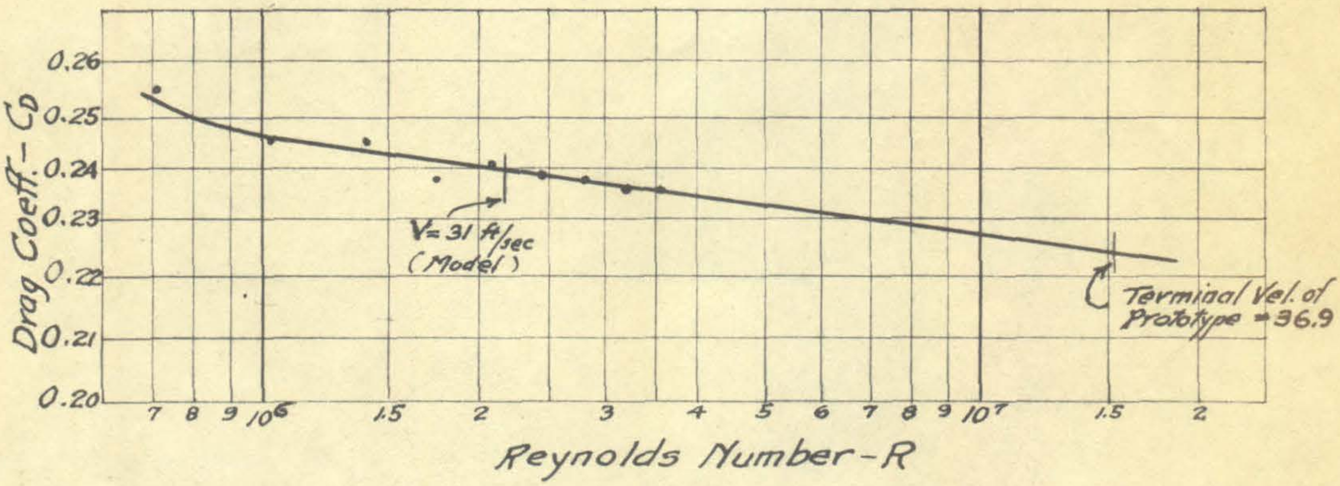


RELATION BETWEEN SUBMERGENCE,
VELOCITY AND CAVITATION PARAMETER

British Type "C" Projectile

CIT-HML
DRG-ND24-1669-LS

Fig. 22



REYNOLDS NUMBER
AND
DRAG COEFFICIENT

British Type "C" Projectile

CIT-HML
DRG-ND 24- 1670-LS

THE HIGH SPEED WATER TUNNEL
at the
CALIFORNIA INSTITUTE OF TECHNOLOGY

APPENDIX A

DEFINITIONS

YAW ANGLE

The angle which the axis of the model makes with the direction of flow. Looking down on the model, yaw angles in a counter-clockwise direction are negative (-) and in a clockwise direction, positive (+).

MOMENTS

Moments tending to rotate the model in a counter-clockwise direction (when looking down on the model) are negative (-), and those causing clockwise rotation, positive (+).

In accordance with this sign convention a moment has a destabilizing effect when it has the same sign as the yaw angle.

In all model tests the moment is measured about the point of support.

Moments about the center of gravity have the symbol, M_{cg}.

DRAG

The force, in pounds, exerted on the model parallel with the direction of flow.

CROSS FORCE

The force, in pounds, exerted on the model normal to the direction of flow. A positive cross force is defined as one acting in the same direction as the displacement of the projectile nose for a positive yaw.

NORMAL COMPONENT

The sum of the components of the drag and cross force acting normal to the axis of the model. The value of the normal component is given by the following:

$$N = (D \sin \psi + C \cos \psi)$$

in which

N = Normal component in lbs

D = Drag in lbs

C = Cross force in lbs

ψ = Yaw angle in degrees

CENTER OF PRESSURE

The point in the axis of the model at which the resultant of all forces acting on the model is applied. This has the symbol (CP).

CENTER-OF-PRESSURE ECCENTRICITY

The distance between the center of pressure (CP) and the center of gravity (CG) expressed as a decimal fraction of the length (L) of the model. The center-of-pressure eccentricity (e) is derived as follows:

$$e = \frac{(L_{cp} - L_{cg})}{L} = \frac{1}{L} \quad \frac{M_{cg}}{N}$$

in which

e = Center-of-pressure eccentricity

L = Length of model in feet

L_{cg} = Distance from nose of projectile to CG in feet

L_{cp} = Distance from nose of projectile to CP in feet

COEFFICIENTS

The three force coefficients used are derived as follows:

Drag coefficient, $$C_D = \frac{D}{\rho \frac{V^2}{2} A_D}$$

Cross force coefficient, $$C_C = \frac{C}{\rho \frac{V^2}{2} A_D}$$

Moment Coefficient, $$C_M = \frac{M}{\rho \frac{V^2}{2} A_D L}$$

in which

D = Measured drag force in lbs

C = Measured cross force in lbs

ρ = Density of the fluid in slugs/cu ft

w = Specific weight of the fluid in lbs/cu ft

g = Acceleration of gravity in ft/sec^2

A_D = Area in sq ft of a cross section at the cylindrical portion of the projectile taken normal to the geometric axis of the projectile

V = Mean relative velocity between the water and the projectile in ft/sec

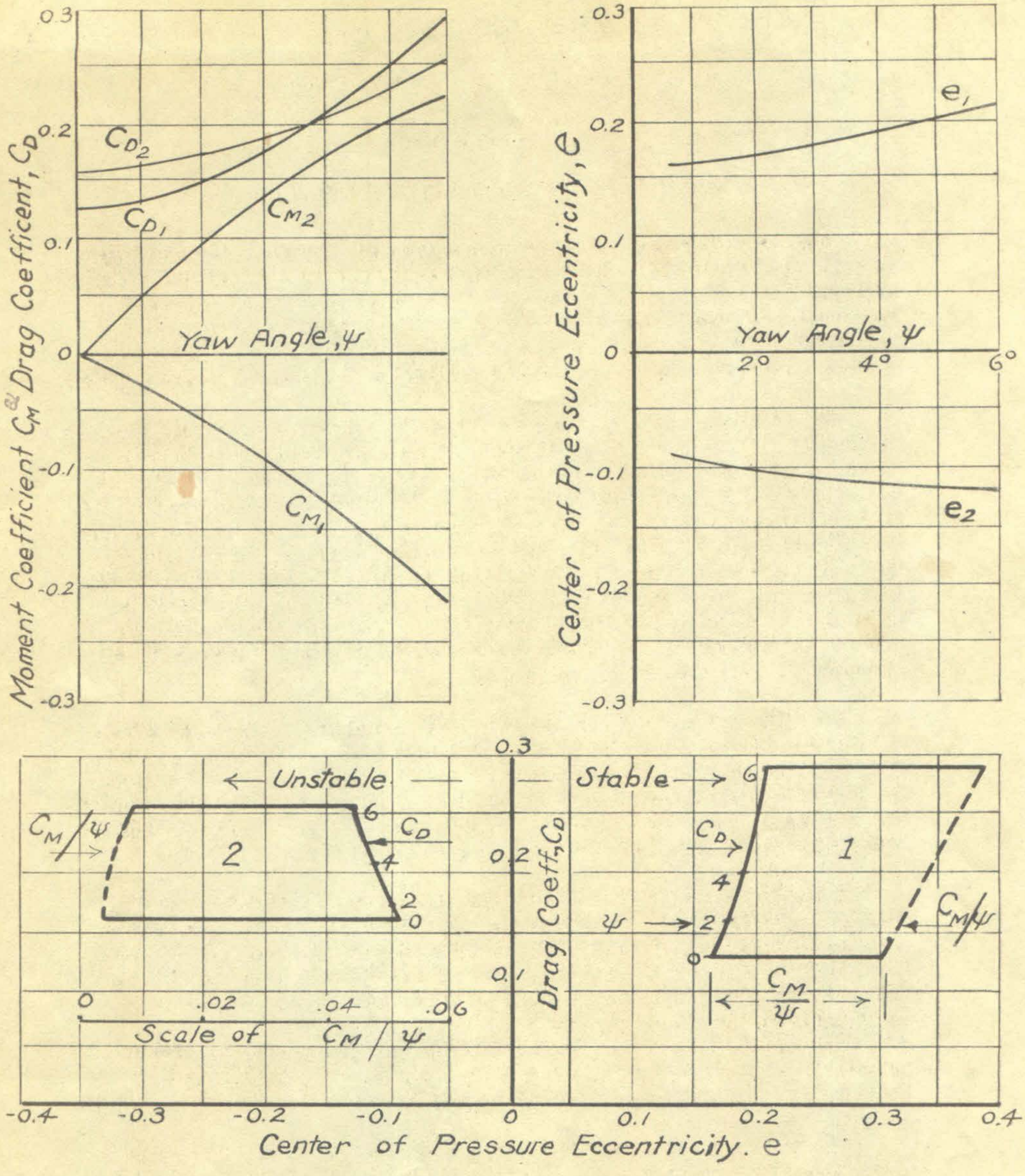
M = moment in foot-lbs measured about any particular point on the geometric axis of the projectile

L = overall length of the projectile in feet

GENERAL DISCUSSION

The curves of force and moment coefficients and of center-of pressure distance plotted as functions of the yaw angle are useful for a discussion of the stability of projectiles. Since these tunnel tests are made under steady flow conditions, the results will only indicate the tendency of the projectile to return to or move away from the equilibrium position after a disturbance. Adopting aerodynamic usage, a projectile is said to be "statically" stable if it tends to return to equilibrium when disturbed. In the discussion of static stability the actual motion following the perturbation is not considered at all. In fact, a projectile may oscillate about the equilibrium position without ever remaining in it. In this case the projectile would be statically stable even though "dynamically" unstable. For a complete discussion of the mode of motion to be expected following a perturbation, the "dynamic" stability, additional information is necessary.

The condition for equilibrium is satisfied if C_M, calculated about the CG is equal to zero. In general, for projectiles with axial symmetry the moment is zero at $\psi = 0°$, so that for equilibrium the projectile is oriented with its axis parallel to the direction of motion. If the projectile is rotated from the equilibrium position so as to give it a positive yaw angle, it is necessary that it have a negative moment coefficient, according to the sign convention adopted, in order that it be statically stable. Thus, a negative slope of the curve, C_M, vs. ψ corresponds to static stability, and a positive slope corresponds to instability. The degree of stability or instability is indicated by the magnitude of the slope. The same conclusions are obtained by interpreting the center-of-pressure curves. For symmetrical projectiles, if the center of pressure falls behind the center of gravity, a restoring moment exists and the projectile is statically stable. If the CP lies ahead of the CG, the moment is non-restoring and the projectile is statically unstable. The degree of stability or instability is indicated by the distance between the center of gravity and center of pressure.



TYPICAL CHARACTERISTIC CHART

The California Institute of Technology---High Speed Water Tunnel.

DRG:-HD24-1671-L

THE HIGH SPEED WATER TUNNEL
at the
CALIFORNIA INSTITUTE OF TECHNOLOGY

APPENDIX B

DESCRIPTION OF CHARACTERISTIC CHART

The attached curve sheet shows typical curves for drag and moment coefficients and, also, center-of-pressure eccentricity, all varying with the yaw angle. Two cases have been assumed, indicated by the subscripts (1) and (2). These curves are selected merely to illustrate method of plotting the chart and do not represent data on the projectile discussed in this report.

In order to obtain a better visualization of the performance indicated by the curves mentioned above, the "Characteristic Chart", shown at the bottom of the sheet, has been devised. In this chart the drag coefficient, C_D, is first plotted against the CP eccentricity, e. On this C_D curve are points opposite which are figures indicating the yaw angle, ψ. This C_D curve shows the variation in drag and CP eccentricity with yaw angle. Also, the position of the curve at the right or left of the vertical axis (+ e or - e) indicates whether or not the projectile is stable or unstable, in other words, whether the CP lies aft or forward of the center of gravity.

On this same chart is plotted the quantity C_M/ψ which gives an indication of the change in the moment coefficient, C_M, with varying yaw angle. This is done by dividing the C_M by the yaw in degrees and plotting these values, C_M/ψ, to a suitable scale, horizontally from the points representing the yaw angle. (For each yaw angle the zero for the C_M/ψ scale is at the C_D curve).

The "Characteristic Chart" is useful as it gives a fairly complete picture of the variation of three important characteristics of the projectile with changes in yaw angle. It is seen that Case 1 has much less increase in drag than Case 2. Also, that the CP eccentricity in Case 1 increases with the yaw and is positive, and therefore, tends to increase stability. In addition to this, the C_M is increasing at an increasing rate, indicating a proportional increase in restoring moment with increasing yaw angles. This is an additional stabilizing factor.

In Case 2 the opposite charadteristics of Case 1 are indicated. Here, there is a greater increase in drag with increase in yaw; also, the CP eccentricity, which is negative, increases with the yaw, thus tending to decrease stability. The change in moment coefficient occurs at a decreasing rate, indicating a proportional decrease in restoring moment with increasing yaw. This is a destabilizing factor.